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# Developing a spatially and temporally explicit solar resource dataset for Great Britain

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**Abstract:** Existing dispatch and infrastructure investment tools for modelling the Scottish energy system do not currently include solar photovoltaic resource. This study describes the development of three spatially and temporally explicit solar resource datasets for use in these models, for domestic, commercial roof-mounted and ground-mounted arrays. They include the whole of Great Britain (GB) and are based on empirical weather data for 2000–2015. They are expected to be a valuable resource for energy system modelling in GB.

## 1 Introduction

Governments around the world are committed to promoting renewable generation as a means of reducing carbon emissions, and this is expected to include a significant increase in solar installations alongside other technologies. The Scottish Government uses some tools to plan routes to achieving decarbonisation targets, including the Scottish Electricity Dispatch Model (SEDM) [1] and Scottish TIMES [2], but these do not currently include robust estimates of solar photovoltaic (PV) resource. There is, therefore, a need to develop spatially and temporally-explicit characterisations of PV resource variability over operating time scales to enhance the existing models.

The SEDM is one of the principal tools for assessing the implications of the ambitious decarbonisation target for electricity in Scotland. A regional electricity dispatch and infrastructure investment model, it has been used to suggest how the network and generation portfolio might be developed to meet future demand within the emissions constraints. It currently includes ‘regional’ time series of wind generation, based on modelled wind speed data for 2001–2010 supplied by the University of Edinburgh based on modelling using the Weather Research and Forecast (WRF) model [3]. There is scope to extend this to include PV data for the same time period.

The new Scottish TIMES model also considers renewable energy resources in its long term least cost optimisation. This considers a typical day for each season, so provides less temporal resolution than the SEDM, but encompasses the whole Scottish energy system – including heat, electricity and transport. It does not currently include data for solar PV, so incorporating it into the model will provide additional information for policy makers.

This paper describes the development of a spatially and temporally explicit solar resource dataset for the whole of Great Britain (GB), but with a focus on Scotland, based on empirical weather data from 2000–2015. This will be used to enhance the SEDM and Scottish TIMES, as well as being incorporated into the University of Edinburgh's advanced unit commitment model of the GB electricity system, to provide greater insight into the complex operating environment of future generating technologies in Scotland, possible co-benefits/dis-benefits and the impacts of variability and intraday flexibility.

## 2 Dataset development

A significant challenge with modelling renewable generation in Scotland is that of modelling the spatial and temporal characteristics of the resource availability. Scotland-specific data is not widely available, and spatial divisions and boundaries are rarely comparable across different models. Measured data is

usually only available as ‘spot’ measurements at isolated sites, so can only be used for a renewable resource estimate if the generator is at this measurement location. (It can, however, be valuable for validating system models.) Electricity dispatch models, such as the SEDM, also require data at a high temporal resolution to properly examine the effects of high-frequency fluctuations in output, and this is rarely available. Furthermore, the renewable energy output is also constrained by the generating technology; for example solar PV is typically mounted on an incline, whereas solar data is typically available as horizontal irradiance. To evaluate the renewable resource across Scotland, the modelled weather data must be converted to energy data according to these constraints.

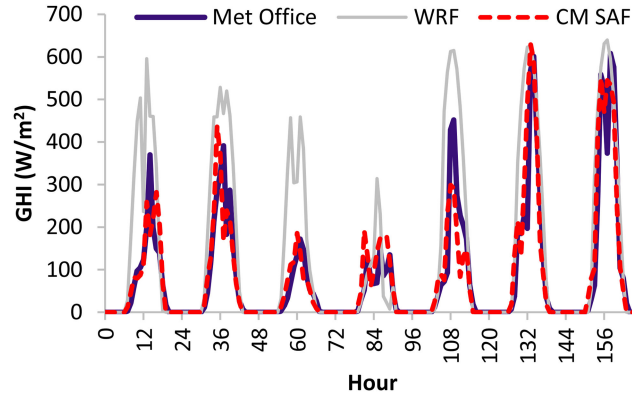
### 2.1 Solar irradiance datasets

The first step in this analysis was to evaluate the available solar irradiance datasets for accuracy and resolution. Three datasets were considered: Modern-Era Retrospective analysis for Research and Applications (MERRA) [4], University of Edinburgh Weather Research and Forecasting (WRF) data [3], and post-processed (CM SAF) satellite weather data from the Meteosat EU meteorological satellite (EUMETSAT) [5]:

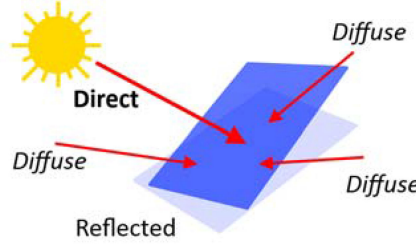
- The MERRA dataset was published by NASA in 1999, covering the period from 1979 to February 2016, with version 2 having been released more recently. It is based on a combination of empirical and modelled data over a  $0.5^\circ \times 0.66^\circ$  grid ( $\sim 55$  km).
- Both the SEDM and Scottish TIMES currently include wind generation profiles based on wind speed data from Edinburgh's WRF model. Solar radiation data for Scotland is also available in this model on a 3 km grid.
- The Satellite Application Facility on Climate Monitoring (CM SAF) uses EUMETSAT data to estimate key irradiance values and provides data on an hourly basis on a  $0.05^\circ \times 0.05^\circ$  latitude and longitude grid ( $\sim 4$  km) for 1983–2015.

A recent study comparing MERRA with CM SAF found that the latter was generally more accurate on an hourly basis and a better fit for GB on data post-1995 [6]. The MERRA dataset was, therefore, disregarded for this study.

The WRF and CM SAF data were validated against historical measured weather data published by the UK Met Office for five sites in Scotland from 2000 to 2010 [7]. It was found that the WRF data had a poor correlation and a systematic bias, being very accurate on sunny days but tending to overestimate on cloudy days (Fig. 1). This was attributed to the choice of radiation transfer model in the simulations; significant improvements in the radiation modelling fidelity of WRF have been seen in more recent versions. In contrast, the CM SAF data, also shown in Fig. 1, was found to



**Fig. 1** Comparison of measured and modelled global horizontal irradiance data at Bishopton (PA7) for the last week of March 2001 [3, 5, 7]



**Fig. 2** Radiation on an inclined plane

match well with the measured data, with an  $R^2$  value over 0.83 at all locations and a bias tending to underestimate insolation by only 3–10 W/m<sup>2</sup> (4–10%).

## 2.2 Adjusting for an inclined plane

The raw solar irradiance datasets provide horizontal irradiance data which must be translated to an incline, considering direct, diffuse and reflected components (Fig. 2). The physics and trigonometry required to translate direct horizontal radiation to an inclined plane is straightforward and based on tilt, orientation, latitude and longitude. It is described by (1), where  $G_{B_i}$  is the direct component on the inclined plane, DNI is the direct normalised irradiance from the CM SAF database, and  $\theta$  is the angle between the Earth–Sun line and the normal to the inclined plane

$$G_{B_i} = \text{DNI} \times \cos \theta \quad (1)$$

Similarly, it is straightforward to calculate the ground-reflected irradiance on the incline ( $G_{R_i}$ ), from the surface incoming shortwave radiation (SIS) in the CM SAF dataset (i.e. global horizontal irradiance), the tilt ( $\beta$ ) and the reflection coefficient of the ground ( $\rho_G$ ), estimated to be 0.2:

$$G_{R_i} = \text{SIS} \times \rho_G \times [(1 - \cos \beta)/2] \quad (2)$$

It is more complicated, however, to translate the diffuse radiation component to the inclined plane. Diffuse radiation is subject to effects such as circumsolar brightening, where the light is brighter near the sun, and horizon brightening, which is the effect of light bending at the horizon. Four models were considered [8]:

- *Isotropic sky* model assumes that diffuse light arrives from all directions equally.
- *Klucher* model is isotropic but corrects to include the effects of brightening in the circumsolar region (near the Sun's disc) and horizon brightening at sunrise/sunset.
- *Hay-Davies* model assumes an isotropic sky where diffuse light intensity varies with direction, based on cloudiness, and includes circumsolar brightening.
- *Reindl* model is like the Hay–Davies model but also includes horizon brightening.

The effect of these diffuse radiation models was systematically tested using the PV generation model in the next section against measured data from 28 sites across Scotland published on the PV output website for 2012–2015 [9]. It was found that all models provided a similar fit in terms of  $R^2$  (typically >0.7) but the isotropic sky model had a significantly lower bias, so was selected for use here. The diffuse irradiance on the inclined plane  $G_{D_i}$  is then given by

$$G_{D_i} = (\text{SIS} - \text{DNI} \times \cos \Phi) \times [(1 + \cos \beta)/2] \quad (3)$$

where  $\Phi$  is the angle between the Earth–Sun line and the vertical.

The total irradiance on the inclined plane is the sum of the three radiance components.

## 2.3 PV generation

The relationship between the output power of a PV array ( $P_{\text{out}}$ ) and the irradiance on the inclined plane ( $G_i$ ) is described by

$$P_{\text{out}} = P_{\text{cap}} \times \epsilon_{\text{rel}} \times G_i / G_{\text{STC}} \times \eta \quad (4)$$

where  $P_{\text{cap}}$  is the total installed capacity of the array,  $G_{\text{STC}}$  is the irradiance under standard test conditions (1000 W/m<sup>2</sup>), and  $\eta$  is the inverter efficiency.  $\epsilon_{\text{rel}}$  is the performance of the PV panels under particular operating conditions relative to those at standard test conditions:

$$\epsilon_{\text{rel}} = 1 + 0.01 T_{\text{coeff}} \times (T_{\text{cell}} - T_{\text{STC}}) \quad (5)$$

where  $T_{\text{coeff}}$  is the temperature sensitivity of the panels (%/°C),  $T_{\text{cell}}$  is the cell temperature (°C) and  $T_{\text{STC}}$  is the standard test temperature (25°C).

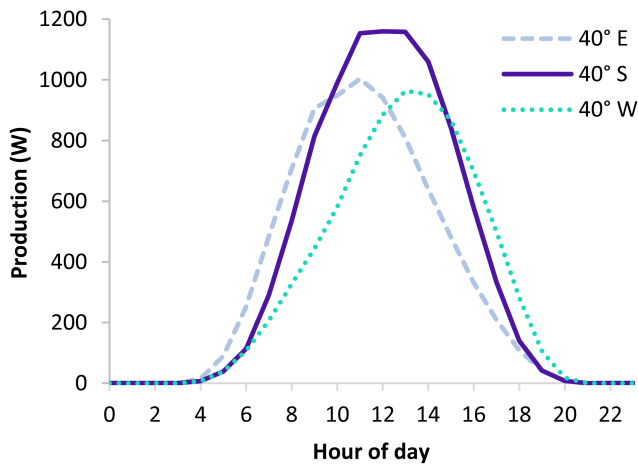
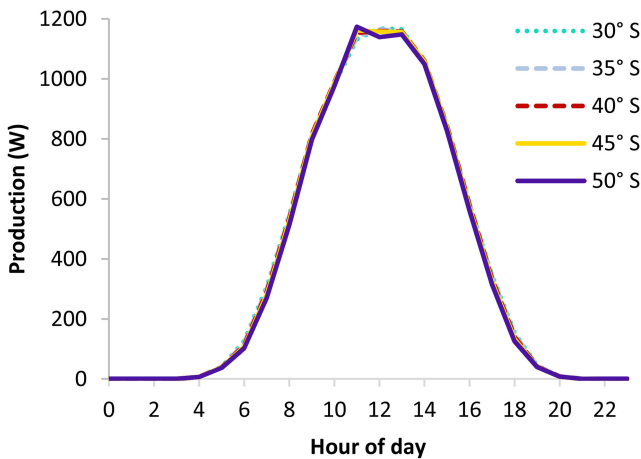
The cell temperature is governed by ambient conditions. Some expressions exist employing a range of meteorological variables, but here the effects of irradiance, temperature and wind speed are used [10]

$$T_{\text{cell}} = 4.3 + 0.943 T_{\text{amb}} + 0.028 G_i - 1.528 U \quad (6)$$

where  $T_{\text{amb}}$  is ambient temperature (°C) and  $U$  is wind speed (m/s). The wind and wind speed were taken from the gridded ERA-

**Table 1** Typical installations for domestic (*D*), commercial roof-mounted (*R*) and ground-mounted arrays (*G*)

	Installed capacity, kW	Orientation	Tilt	Inverter capacity, kW	Inverter efficiency, %
<i>D</i>	4	27% SW, 49% S, 24% SE	35°	3.68	96
<i>R</i>	10	27% SW, 49% S, 24% SE	35°	2 × 5	96.5
<i>G</i>	5	S	35°	100 × 50	98.5

**Fig. 3** Impact of orientation on average daily output from 2014 of a 4 kW array at a 40° tilt near Elgin (IV36)**Fig. 4** Impact of tilt on average daily output from 2014 of a 4 kW array orientated due south near Elgin (IV36)

Interim dataset [11].  $P_{out}$  was capped according to the inverter capacity.

#### 2.4 Typical installations and existing capacity

The energy system models require solar power output data expressed per unit of capacity. As both the SEDM and Scottish TIMES are used to model potential future expansion of solar PV, the power profiles need to be independent of existing installed capacity (although data on the existing capacity is also required). A small number of ‘typical’ installations were therefore defined, with a given capacity, orientation, tilt and inverter efficiency.

The existing portfolio of solar PV in GB was extracted from available government data and found to generally fall into three distinct types: domestic (*D*), commercial roof-mounted (*R*) and commercial ground-mounted (*G*) [12, 13]. A typical installation for each type was defined, based on the median capacities of the existing installations, and typical panel and inverter specifications (Table 1). Inverters were generally sized to match the installed capacity, except in the case of the domestic array which has a smaller inverter due to regulations governing the maximum power injection into each phase of the network.

An analysis of the impact of panel orientation and tilt on power output profile found that orientation (Fig. 3) was much more

significant for the magnitude and timing of power generation than the angle of tilt (Fig. 4), due to the relatively large contribution of diffuse light. Therefore an appropriate combination of orientation is important for simulating aggregate generation.

It was assumed that the typical ground-mounted array is oriented due south, while the domestic and roof-mounted arrays are oriented 27% southwest, 49% south and 24% southeast according to the distribution of orientations of available data on existing installations in the UK [9]. The typical tilt was approximated as 35°, the median tilt of all UK installations. (This assumption was tested by re-running the validation described in Section 2.2 for 28 specific installations, but forcing the tilt to be 35°, and it was found that the  $R^2$  value was unchanged and there was a small increase in bias.)

Hourly power output profiles for each of these three types of typical installations were generated for all 2880 postcode districts in GB, based on weather data from 2000 to 2015.

#### 2.5 Existing capacity

The energy system models also require data on the existing and potential installed capacity of solar PV across GB. Data on existing installations was taken from information published by the UK government in two different datasets: the Feed-in-Tariff (FIT) Installation Report, and the renewables planning database. The first of these gives a breakdown of renewable installations that have achieved FIT accreditation, including solar PV installations with a capacity of up to 5 MW [12]. The second track the progress of new renewable energy projects that have applied for planning permission, and only includes installations sized at 1 MW or greater [13].

Information from these datasets was combined and any duplicates were removed. Only installations that were completed before December 2016 were included, as this was the latest complete year at the time of analysis. This data was then scaled such that the total installed capacity for each local authority matched government totals in a third dataset [14]. The data was then aggregated across all 2880 postcode districts (e.g. ‘EH9’) in GB, and the resulting dataset is illustrated in Fig. 5.

It can be seen that the installations are concentrated in central and southern England. Generally, the domestic and roof installations are concentrated in the urban areas, while there is a significant existing capacity of ground-mounted solar farms across rural areas. In Scotland, however, there are only very few solar farms, and the existing capacity is dominated by domestic installations in the central belt and along the east coast.

### 3 Analysis results

Although the primary purpose of this work was to produce a solar resource dataset for use in the energy system modelling in Scotland and GB, some preliminary analyses have been carried out on the data.

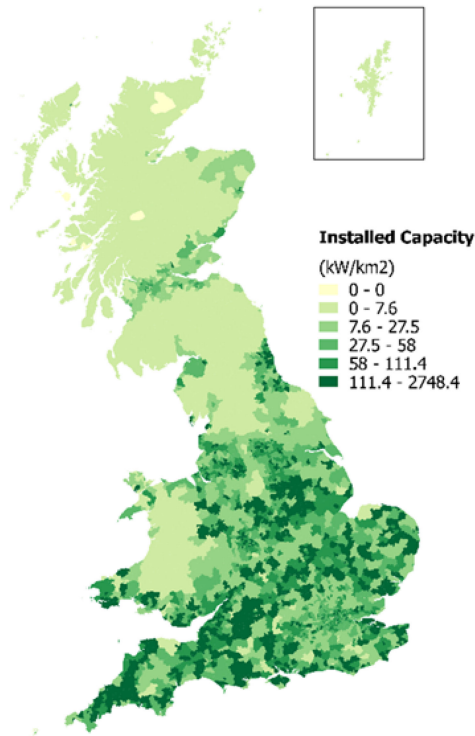
#### 3.1 Inter-annual variability

The modelled PV output has a substantial variability year to year, as illustrated in Fig. 6. The long 16-year dataset is therefore likely to provide a good overview of ‘typical’ outputs across a range of different weather patterns.

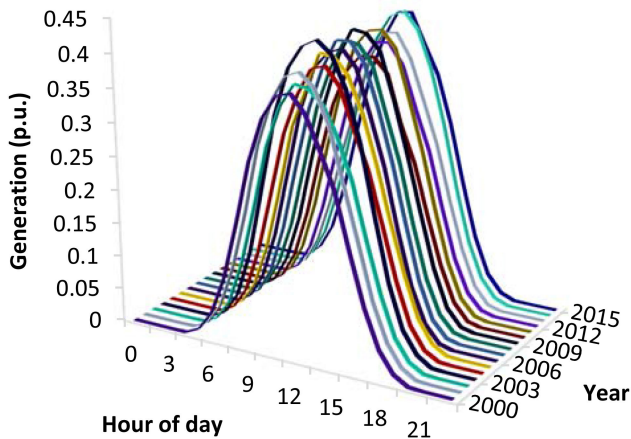
#### 3.2 Spatial variation

The spatial variation in mean output is illustrated in Fig. 7, and it can be seen that the north and west of Scotland have a 40% lower mean energy production than the south coast of England.





**Fig. 5** Distribution of existing installed PV capacity across GB, normalised for the size of each postcode district



**Fig. 6** Mean hourly output for a roof-mounted array near Ipswich, England (IP14)

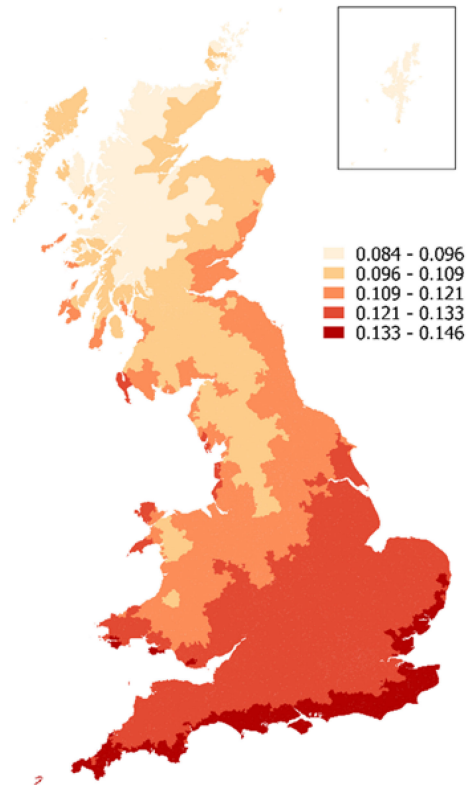
This dataset, however, contains data at an hourly resolution for energy systems modelling, and Fig. 8 shows the maximum instantaneous output for each postcode across the country. It can be seen that in parts of north-western Scotland this is almost as high as in southern England, which would have implications for electricity dispatch in the area.

### 3.3 Implications of aggregation

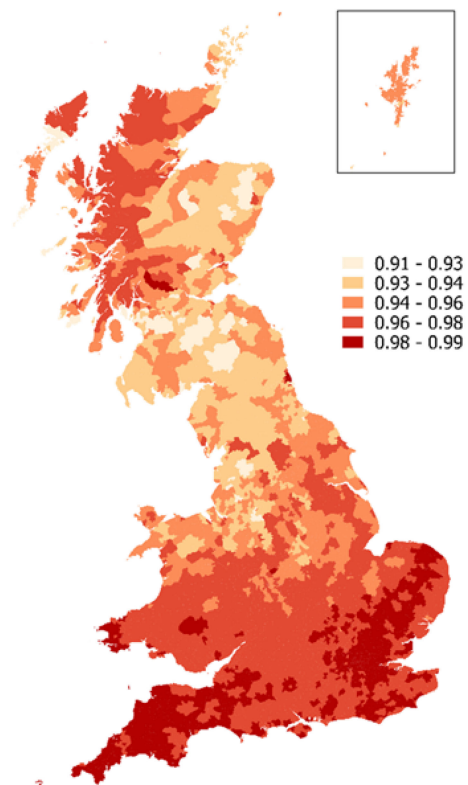
The data must be aggregated to provide inputs to the energy system models. Each model requires data at a different spatial and temporal resolution; for example the SEDM model divides GB into 14 zones, while the Scottish TIMES model considers only Scotland as one zone (although there is scope to further subdivide it for a given type of generation). This has a significant smoothing effect on the data.

## 4 Conclusions

A set of solar PV output datasets have been developed for all 2880 postcode districts in GB, at hourly resolution, for three different types of typical array: domestic roof-mounted, commercial roof-



**Fig. 7** Mean output (per unit) from 2000 to 2015 across GB for a typical roof-mounted array



**Fig. 8** Maximum hourly output (per unit) between 2000 and 2015 across GB for a typical roof-mounted array

mounted and ground-mounted. Based on the best available data on weather covering 16 years of weather patterns, these are expected to be a valuable resource for energy, infrastructure investment and electricity dispatch models. They are already being incorporated into the models for use by the Scottish Government.

## 5 Acknowledgments

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